CHROMOMAGNETIC AND CHROMOELECTRIC DIPOLE MOMENTS OF THE TOP QUARK IN THE 4GTHDM

ALAN IGNACIO HERNÁNDEZ JUÁREZ, GILBERTO TAVARES VELASCO AND AGUSTÍN MOYOTL ACUAHUITL

FCFM, BUAP

SILAFAE
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INTRODUCTION

- Since its discovery in 1995 the top quark has played a special role in the study of the phenomenology of the standard model (SM).

- The LHC is a top quark factory, then the study of the new contributions to the chromomagnetic dipole moment (CMDM) and chromoelectric dipole moment (CEDM) of the top quark is a topic worth studying as they could be at the reach of experimental measurement in the near future.

- A nonzero CEDM is a clear evidence of CP violation.

- CP violation in necessary to explain the baryon asymmetry of the universe (Sakharov's criteria).

INTRODUCTION

- In the SM, the complex phase of the CKM matrix gives rise to CP violation but it is still not enough to explain the baryon asymmetry.

- New sources of CP violation beyond the SM are required.

- The CMDM and CEDM can be induced via the following Lagrangian

$$\mathcal{L} = -\frac{g_s T^a}{2}\bar{t}\,\frac{a_t}{2m_t}\sigma^{\mu\nu}\,tG^a_{\mu\nu} - \frac{T^a}{2}\bar{t}\,i\sigma^{\mu\nu}\gamma^5 d_t\,tG^a_{\mu\nu},$$

- Where a_t is the CMDM, while d_t is the CEDM.

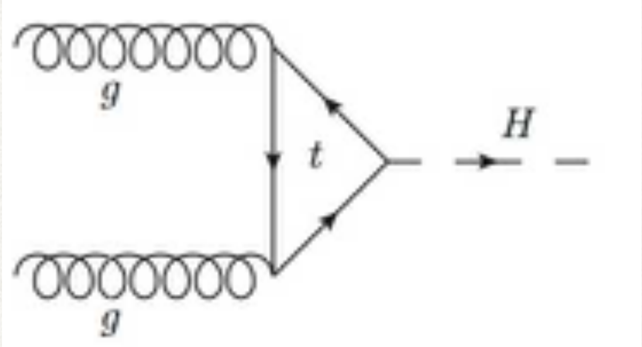
4GTHDM

- The 4GTHDM is a variation of a THDM type-II which introduces a fourth generation of fermions. (PhysRevD.84.053009)

- A model with a fourth generation of SM-like quarks was studied in the past (SM4).

- Unfortunately, the SM4 is not consistent with the Higgs production at the LHC.

- In the 4GTHDM the theoretical prediction for Higgs boson production at the LHC remains unchanged. (PhysRevD.86.115008)



4GTHDM

- The Yukawa Lagrangian of the quark sector can be written as follows:

$$\mathcal{L}_Y = -\overline{Q}_L \left(\Phi_\ell \mathbf{F} \cdot \left(\mathbf{I} - \mathbf{I}_d^{\alpha_d \beta_d}\right) + \Phi_h \mathbf{F} \cdot \mathbf{I}_d^{\alpha_d \beta_d}\right) d_R$$
$$- \overline{Q}_L \left(\tilde{\Phi}_\ell \mathbf{G} \cdot \left(\mathbf{I} - \mathbf{I}_u^{\alpha_u \beta_u}\right) + \tilde{\Phi}_h \mathbf{G} \cdot \mathbf{I}_u^{\alpha_u \beta_u}\right) u_R + \mathrm{H.c.},$$

- We focus in the 4GTHDM-l, where $(\alpha_b, \beta_{b'}, \alpha_t, \beta_{t'}) = (0,1,0,1) : \Phi_h$ gives masses to the fermions of the fourth family only, whereas Φ_ℓ gives masses to the remaining fermions.

4GTHDM

- Flavor changing neutral currents (FCNCs) in the 4GTHDM arise at the tree level in the scalar sector and can be written as

$$\mathcal{L} = \frac{g}{2m_W} f^\phi \bar{q}_i \left(S^\phi_{ij} + P^\phi_{ij}\gamma_5 \right) q_j \phi + \text{H.c.},$$

Where i (j) runs over up (down) quarks for h^0, H^0 and A^0 , while for $H^\pm$ runs over up (down) quarks.

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ϕ	f^ϕ	S^ϕ_{ij}	P^ϕ_{ij}
h^0	$\frac{c_\alpha}{s_\beta} + \frac{s_\alpha}{c_\beta}$	$\frac{m_{q_i}}{f^\phi_\beta}\frac{s_\alpha}{c_\beta}\delta_{ij} - f^+_{ij}$	$-f^-_{ij}$
H^0	$\frac{c_\alpha}{c_\beta} - \frac{s_\alpha}{s_\beta}$	$-\frac{m_{q_i}}{f^\phi_\beta}\frac{c_\alpha}{c_\beta}\delta_{ij} + f^+_{ij}$	f^-_{ij}
A^0	$2iI_q(t_\beta + \frac{1}{t_\beta})$	f^-_{ij}	$-\frac{m_{q_i}}{f^\phi_\beta} t_\beta \delta_{ij} + f^+_{ij}$
$H^\pm$	$\frac{2}{\sqrt{2}}$	$\frac{1}{2} t_\beta U_{ij}(m_{d_j} - m_{u_i}) + h^-_{ij}$	$\frac{1}{2} t_\beta U_{ij}(m_{d_j} + m_{u_i}) - h^+_{ij}$

- U_{ij} are entries of the new 4x4 CKM matrix, while I_q is the weak isospin.

4GTHDM

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- Where i and j runs over up (down) quarks for h^0, H^0 and A^0 , while for $H^\pm$ runs over up (down) quarks.

ϕ	f^ϕ	S^ϕ_{ij}	P^ϕ_{ij}
h^0	$\frac{c_\alpha}{s_\beta} + \frac{s_\alpha}{c_\beta}$	$\frac{m_{q_i}}{f^\phi_\beta}\frac{s_\alpha}{c_\beta}\delta_{ij} - f^+_{ij}$	$-f^-_{ij}$
H^0	$\frac{c_\alpha}{c_\beta} - \frac{s_\alpha}{s_\beta}$	$-\frac{m_{q_i}}{f^\phi_\beta}\frac{c_\alpha}{c_\beta}\delta_{ij} + f^+_{ij}$	f^-_{ij}
A^0	$2iI_q(t_\beta + \frac{1}{t_\beta})$	f^-_{ij}	$-\frac{m_{q_i}}{f^\phi_\beta}t_\beta\delta_{ij} + f^+_{ij}$
$H^\pm$	$\frac{2}{\sqrt{2}}$	$\frac{1}{2}t_\beta U_{ij}(m_{d_j} - m_{u_i}) + h^-_{ij}$	$\frac{1}{2}t_\beta U_{ij}(m_{d_j} + m_{u_i}) - h^+_{ij}$

- U_{ij} are entries of the new 4x4 CKM matrix, while I_q is the weak isospin.

4GTHDM

- $f^{\pm}_{ij} = \frac{1}{2}\left(m_{q_i}\Sigma^{q}_{ij} \pm m_{q_j}\Sigma^{q*}_{ji}\right)$ with $q = u\ (d)$ for up (down) quarks.

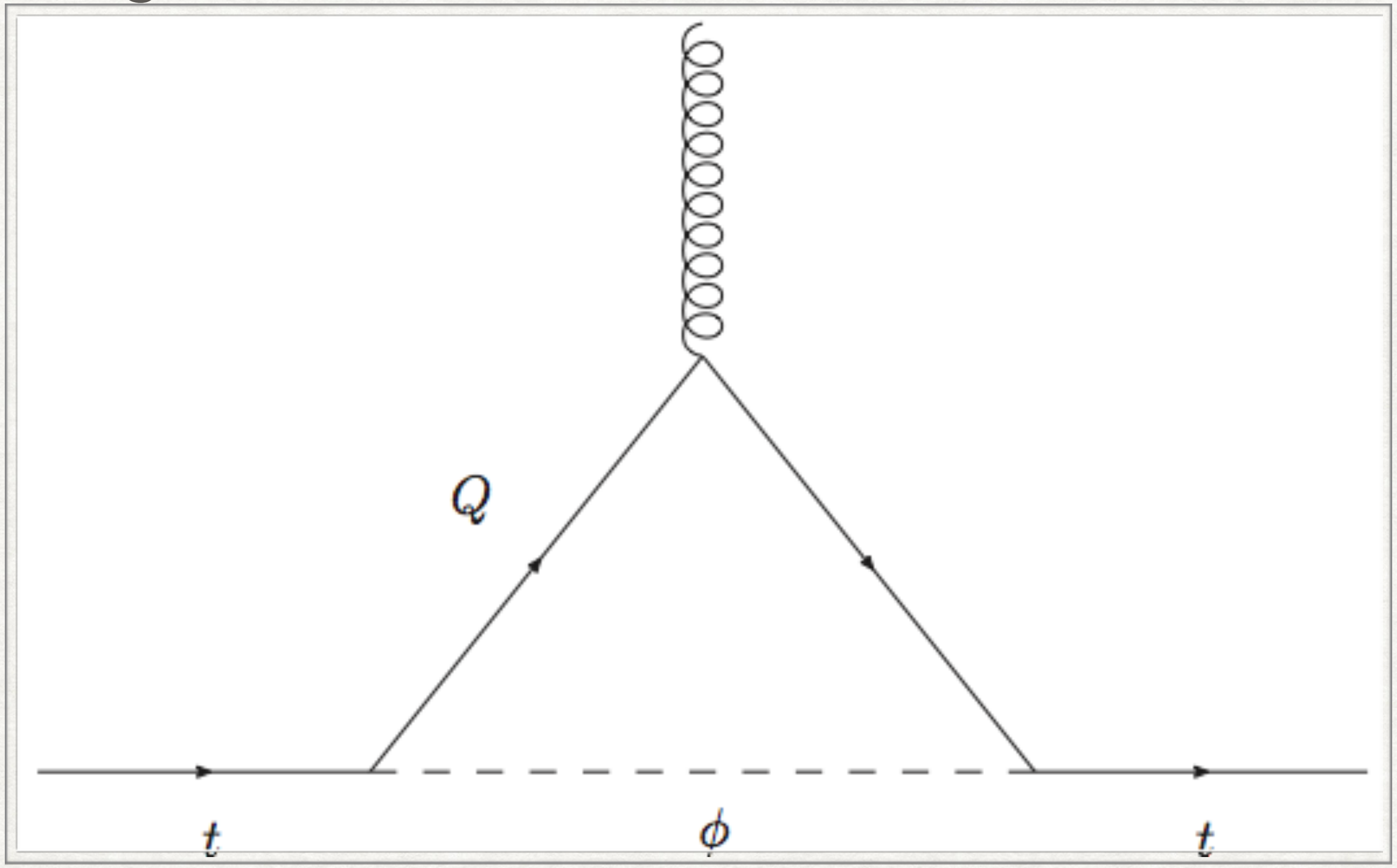
  $h^{\pm}_{ij} = \frac{1}{2}(t_\beta + \frac{1}{t_\beta})(m_{u_k}\Sigma^{u*}_{ki}U_{kj} \pm m_{d_k}\Sigma^{d}_{kj}U_{ik})$

- $\Sigma^{u,d}_{ij}$ are entries of the new complex 4x4 mixing matrices.

$$\mathbf{\Sigma}^{u,d} \simeq \left(\begin{array}{c|cc} \mathbf{0} & \multicolumn{2}{c}{\mathbf{0}} \\ \hline \mathbf{0} & \left|\epsilon_{u,d}\right|^2 & \epsilon^*_{u,d}\left(1-\frac{\left|\epsilon_{u,d}\right|^2}{2}\right) \\ & \epsilon_{u,d}\left(1-\frac{\left|\epsilon_{u,d}\right|^2}{2}\right) & \left(1-\frac{\left|\epsilon_{u,d}\right|^2}{2}\right) \end{array}\right),$$

CMDM AND CEDM IN THE 4GTHDM

- The CMDM and CEDM of the top quark arise through the generic Feynman diagram



- Where $Q = t, t'$ for h^0, H^0 and A^0, whereas $Q = b, b'$ for $H^{\pm}$.

CMDM AND CEDM IN THE 4GTHDM

- The contributions to CMDM and CEDM are

$$a_t^\phi(m_Q) = \left(\frac{g}{2r_W}\right)^2 \frac{|f_\phi|^2}{8\pi^2}\left(|\tilde{S}_{tQ}^\phi|^2 F(r_Q, r_\phi) + |\tilde{P}_{tQ}^\phi|^2 F(-r_Q, r_\phi)\right),$$

$$d_t^\phi(m_Q) = \frac{g_s}{m_t}\left(\frac{g}{2r_W}\right)^2 \frac{|f_\phi|^2}{8\pi^2}\mathrm{Im}(\tilde{S}_{tQ}^\phi \tilde{P}_{tQ}^{\phi *})G(r_Q, r_\phi),$$

- Where

$$F(x,y) = \int_0^1 dz \frac{(1-z)^2(z+x)}{(1-z)(x^2-z)+zy^2},$$

$$G(x,y) = x\int_0^1 dz \frac{(1-z)^2}{(1-z)(x^2-z)+zy^2},$$

$r_a = m_a/m_t$, $\tilde{S}_{ij}^\phi = S_{ij}^\phi/m_t$, and $\tilde{P}_{ij}^\phi = P_{ij}^\phi/m_t$

CMDM AND CEDM IN THE 4GTHDM

- The equation for CMDM contribution can be reduced to SM contribution

$$a_t^{h^0_{\mathrm{SM}}} = \frac{G_F m_t^2}{4\sqrt{2}\pi^2} \int_0^1 dz \frac{(1+z)(1-z)^2}{(1-z)^2 + z r^2_{h^0_{\mathrm{SM}}}},$$

- Numerically we obtain

$$a_t^{h^0_{\mathrm{SM}}} = 3.78 \times 10^{-3}$$

CMDM AND CEDM IN THE 4GTHDM

- The parameter space is taken as

Parameter	Value
$m_{b'}, m_{t'}$	$350 - 600$ GeV
$\Delta_{t'-b'}$	120 GeV
m_ϕ	400–1000 GeV
$\lvert U_{tb}\rvert, \lvert U_{t'b'}\rvert$	0.99
$\lvert U_{t'b}\rvert, \lvert U_{tb'}\rvert$	0.1
$\rho_{t'b}$	0
$\lvert\epsilon_t\rvert, \lvert\epsilon_b\rvert$	0.1, 0.01
$\rho_{tb'}, \delta_t, \delta_b$	$\pi/2$, $\pi/4$, $\pi/4$

- And we consider two scenarios consistent with LHC Higgs data

$$\text{i)}\ \ (t_\beta, c_{\beta-\alpha}) = (10, 0.19).$$

$$\text{ii)}\ \ (t_\beta, c_{\beta-\alpha}) = (5, 0.4).$$

CMDM AND CEDM IN THE 4GTHDM

- The new physics contribution to the CMDM is given as follows

$$\delta a_t^{\rm 4GTHDM} = a_t^{\rm 3rd} + a_t^{\rm 4th},$$

- We define

$$a_t^{\rm 3rd} = \delta a_t^{h^0}(m_t) + \sum_{\phi=H^0,A^0} a^{\phi}(m_t) + a^{H^\pm}(m_b),$$

$$a_t^{\rm 4th} = \sum_{\phi=h^0,H^0,A^0} a^{\phi}(m_{t'}) + a^{H^\pm}(m_{b'}).$$

- Where $\delta a_t^{h^0}(m_t) = a_t^{h^0}(m_t) - a_t^{h^0_{\rm SM}}$

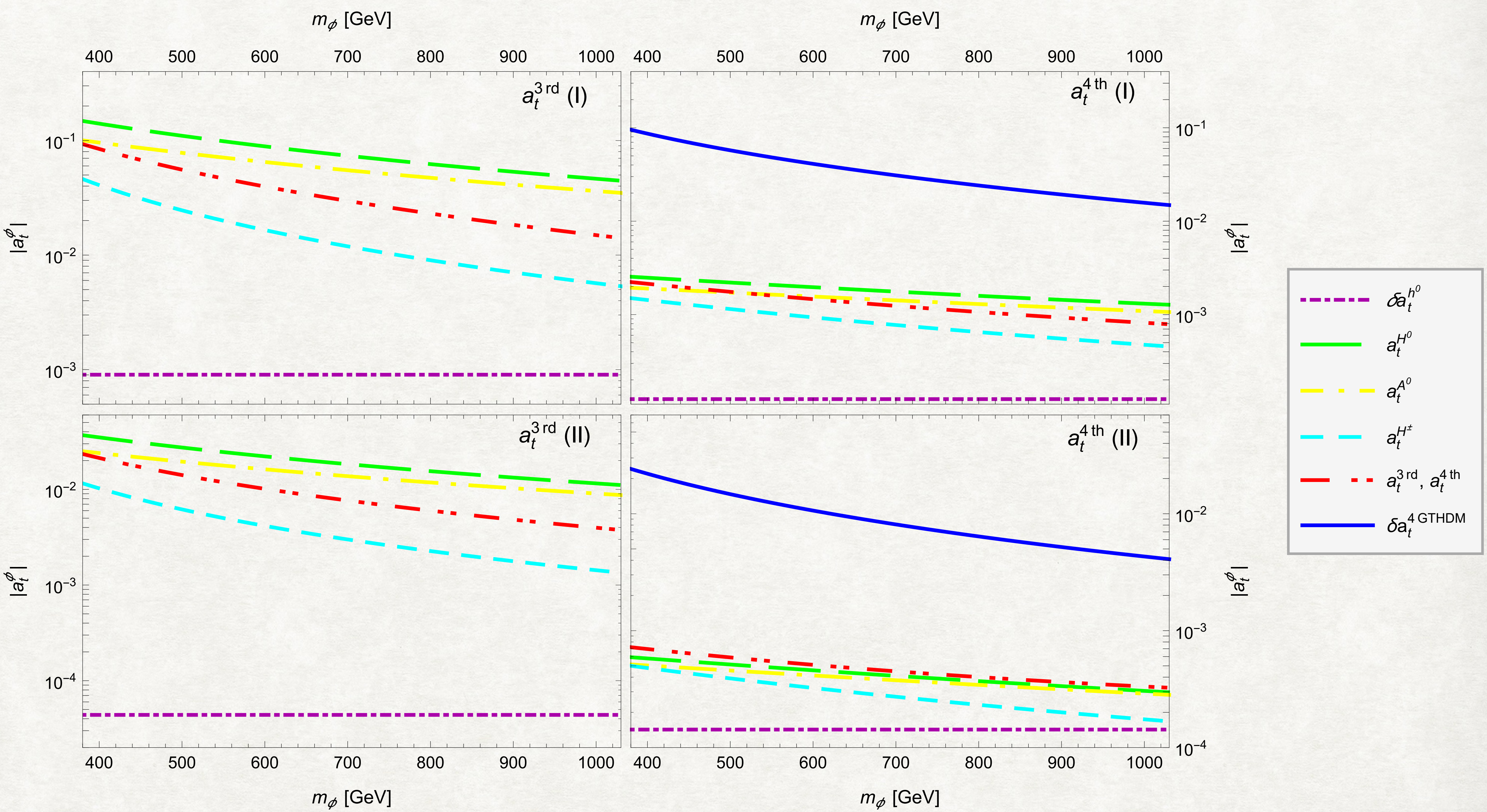
CMDM AND CEDM IN THE 4GTHDM

- The 4GTHDM contribution to the top quark CEDM is

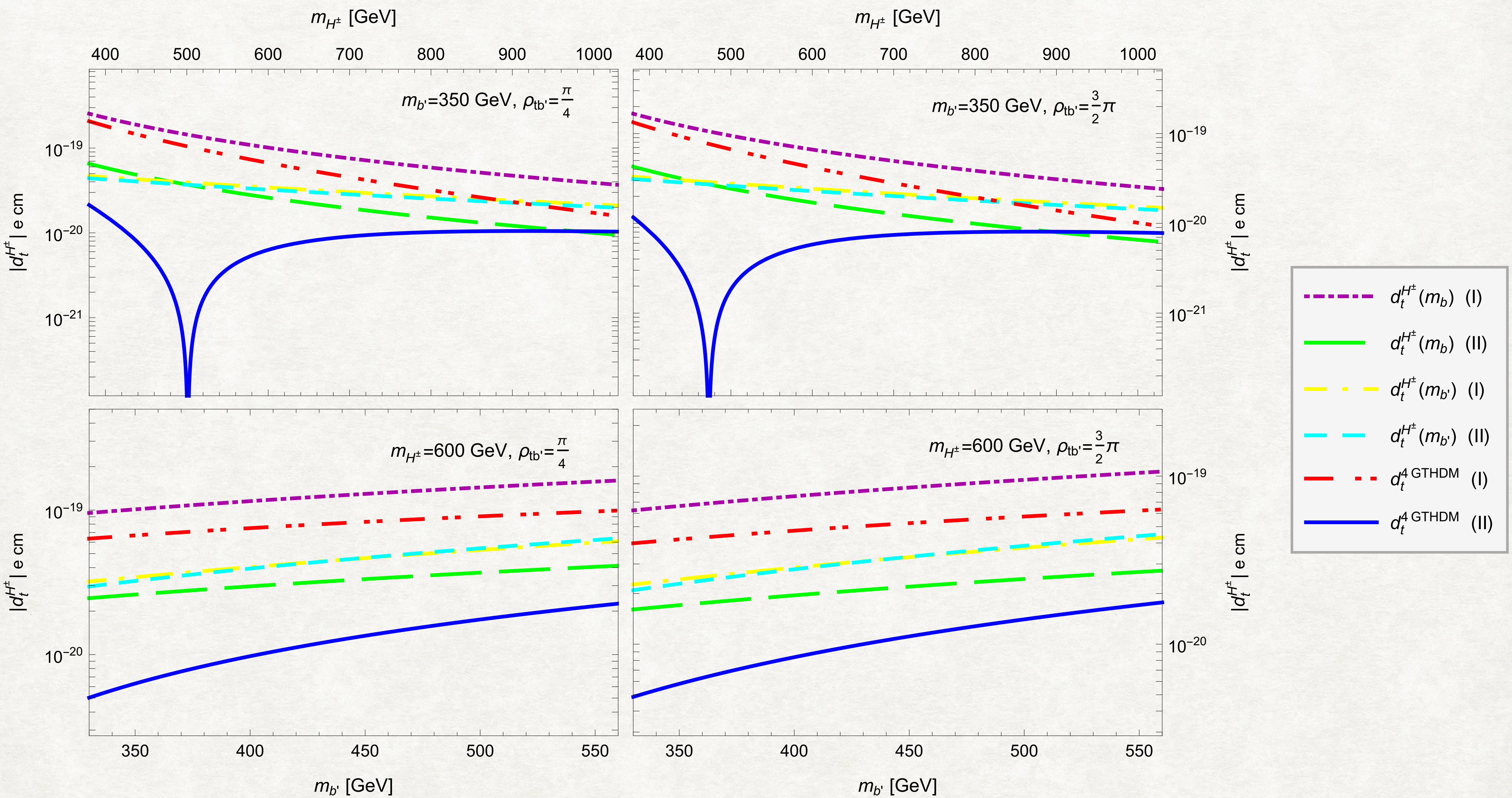
$$d_t^{\rm 4GTHDM} = d_t^{H^\pm}(m_b) + d_t^{H^\pm}(m_{b'}).$$

- Contributions from the neutral scalars bosons to CEDM vanishes due to hermiticity of the mixing matrix $\Sigma^{u,d}$. There is only contribution from the charged scalar boson.

CMDM AND CEDM IN THE 4GTHDM



CMDM AND CEDM IN THE 4GTHDM



CMDM AND CEDM IN THE 4GTHDM

Model	a_t	d_t [ecm]
SM	10^{-2}	
THDMs	10^{-3}–10^{-1}	10^{-20}
4GTHDM	10^{-2}–10^{-1}	10^{-20}–10^{-19}
MHDMs		$< 10^{-19}$
331	10^{-5}	
Technicolor	10^{-2}	
Extra dimensions	10^{-3}	
Little Higgs	10^{-6}	
MSSM	10^{-1}	$< 10^{-19} - 10^{-20}$
Unparticles	10^{-2}	
Vector-like Multiplets		10^{-19}

CONCLUSIONS

- A fourth generation of fermions is still consistent with the 125 GeV Higgs measured in 2012 in the framework of the 4GTHDM.
- New sources of CP violation are required in order to explain baryon asymmetry of the universe.
- We obtain contributions of order $10^{-2} - 10^{-1}$ for the CMDM and order $10^{-20} - 10^{-19}\mathrm{e} \cdot \mathrm{cm}$ for the CEDM.
- The contributions arising from the 4GTHDM can be larger than those predicted by the usual THDM.

- Thank you!